Saccades and fixations in children with delayed reading skills

Running head: Eye movements in delayed reading skills

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Abstract

Purpose: Previous studies have reported that eye movements differ between good/average and poor readers. However, these studies have been limited to investigating eye movements during reading related tasks and thus, the differences found could arise from deficits in higher cognitive processes involved in reading rather than oculomotor performance. The purpose of the study is to determine the extent to which eye movements in children with delayed reading skills are different to those obtained from children with good/average reading skills in non-reading related tasks.

Methods: After a screening optometric assessment, eye movement recordings were obtained from 120 children with delayed reading skills and 43 children without delayed reading skills (4-11 years) using a Tobii TX300 eye tracker. Cartoon characters were presented horizontally from -20° to +20° in steps of 5° to study saccades. An animated stimulus in the center of the screen was presented for 8 seconds to study fixation stability. Saccadic main sequences, and the number and amplitude of the saccades during fixation were obtained for each participant. The children with delayed reading skills (n=43) were unmasked after data collection was completed. Medians and quartiles were calculated for children with and without delayed reading skills.

Results: Independent t-tests with Bonferroni correction showed no significant differences in any of the saccadic main sequence parameters (Slope, Intercept, A, n and Q ratio) between children with and without delayed reading ($p>0.01$). Similarly, no significant differences were found in the number of saccades and their amplitude during the fixation task between the two groups ($p>0.05$). Further, none of the optometric parameters assessed (visual acuity, refractive error, ocular alignment, convergence, stereopsis and accommodation accuracy) were found to be associated with delayed reading skills ($p>0.05$).

Conclusions: Eye movements in children with delayed reading skills are quantitatively similar to those found in children without delayed reading skills. None of the optometric parameters studied were found to differ between the two groups of children. These findings suggest that in these children, delayed reading skills are not associated with eye movement and/or gross visual deficits.

Introduction

Typically, during reading, our eyes move along the lines of text by performing a series of saccades of different amplitude and direction, interspaced with fixations of variable duration. Generally, the saccades are forward saccades so the eyes move and fixate from one word to the next, but they occasionally move backwards to re-fixate a previous word or move to the following text line. Saccades and fixations are very important components of reading as they provide the first step to extracting the visual information from the text and not surprisingly, there is an extensive literature investigating saccadic eye movements and fixations in individuals with reading difficulties.[1-8]

Eye movement behaviour during reading is known to differ between good and poor readers.[e.g 1, 4, 6] Several early studies found that, during reading, non-skilled readers show more fixations, longer fixation durations and more regressions than skilled readers.[4, 6, 9, 10] Lefton et al. (1979)[4] further reported an increased variability in the number of saccades, number of fixations and the duration of the fixation within a group of poor readers compared to good readers of the same age. Perhaps the most interesting finding was that, while good/average readers showed a very similar eye movement strategy for each line of text (similar number of saccades and fixations and duration of fixations), poor readers performed very differently in each line of text and paragraph. Consequently, poor readers showed a relatively unstructured and disorganised eye movement strategy during reading.[4]

Twenty-five years ago, the dominant view was that eye movements during reading were independent of the linguistic and lexical characteristics of the text.[11] Therefore, eye movement disorders were often proposed to be the cause of delayed reading skills. Later research has changed this view, and it is now clear that parameters such as fixation time and the amplitude of saccades during reading are strongly influenced by the text characteristics[11] as well as the linguistic skills of the reader.[12] Hence, it can be argued that the differences found in eye movements during reading in poor readers, can arise from the text linguistic, syntactic and lexical characteristics or even from text difficulty rather than from poor eye movement control or even from both. This argument might

be key in a child population, as children, especially those learning to read, are less experienced with texts, are less familiar with the common words that adults tend to skip when reading, and have a limited vocabulary compared to adults.

Few studies have evaluated saccades and fixations in individuals with delayed/poor reading skills during non-reading tasks. Moreover, the results from these studies are inconclusive as the findings have not been consistent. For instance, some studies [13, 14] have supported the early results from Pavlidis (1985)[15] showing eye movement differences in children with dyslexia and controls in non-reading eye movement tasks. In contrast, other studies have shown no differences in eye movements during non-reading tasks in individuals with dyslexia[16-18] and poor readers[2, 19] compared to age-matched controls. Hence, the relationship between saccades, fixations and reading performance remains unclear. First, it has already been proposed that oculomotor ability is not the principal cause of reading difficulties,[19, 20] and the multifactorial nature of reading difficulties implies that saccadic control and/or fixation stability could be one, but not the only, factor hampering reading in a population of poor readers.[10, 20, 21] Consistent with this, most studies assessing eye movements in poor readers have often not obtained any optometric or vision measure other than the eye movement recordings.[e.g. 1, 2, 13, 15, 22] Visual aspects such as accommodation, refractive error and vergence may interfere with reading performance.[e.g. 23, 24] If these are not assessed, it cannot be determined if there are also contributing to the reading problem in an individual. Second, as most studies evaluating saccades and fixations in poor readers have focussed on assessing these type of eye movements during reading tasks, it is difficult to differentiate an atypical eye movement behaviour arising from oculomotor control difficulties from one arising from the inherent text characteristics. Third, further research is needed as studies evaluating saccades in children with dyslexia and delayed reading during non-reading tasks have not yielded consistent findings.

Finally, it us unknown how many children have delayed reading skill as a result of poor oculomotor control. As a consequence, eye care professionals are frequently faced with children considered to be at risk of eye movement difficulties, who are referred by educational professionals (e.g. psychologists) and health care professionals (e.g. occupational therapists and general practitioners) on the grounds of “poor tracking”,

skipping words and losing their place when reading.[25, 26] The purpose of this study is to investigate differences in saccades and fixations in non-reading based tasks (i.e. pure oculomotor control tasks) between primary school age children with and without delayed reading skills. The saccadic main sequence parameters were chosen to assess saccadic performance as these provide information on the basic dynamics of the saccadic eye movements. Saccadic main sequences have been studied in typcial developing children,[e.g. 27, 28] and atypical children,[e.g. 29, 30] but we are not aware of any study investigating these in children with delayed reading. Saccadic latency and variability were not studied in here, as these have been suggested to provide information on visual processing, but not on the actual quality of the saccades.[31] The number of saccades (i.e. intrusive saccades) during the fixation task and the amplitude of such saccades were chosen to quantify fixation stability, as these have been previously studied in typical developing children,[32, 33] and children with dyslexia.[34] The results of the optometric tests were compared as secondary outcomes. Our prediction is that children with delayed reading skills would have normal saccadic and fixation control during non-reading related tasks. This prediction is based on the view that eye movement performance during reading is largely influenced by the text characteristics, and the linguistic skills of the reader. Therefore, abnormal eye movement behaviour during reading in children with delayed reading skills would indicate deficits related to speech and language and not oculomotor control deficits.

Methods

Participants

Invitation letters were posted to 11 schools in or near Cardiff. Two schools agreed to take part. The protocol was approved by the School of Optometry and Vision Sciences Ethics and Audit Committee and was designed in accordance with the Declaration of Helsinki. Information sheets and consent forms were sent to all parents. One school was city based with a multi-ethnic population; the teachers selected 34 children from different age groups at random whose parents consented to take part in the study. The teachers involved in the selection of participants were not aware of the nature of the study until after the selection was made. This measure was taken in order to control the skewness of the sample. Only the children who were chosen by the teacher were invited to participate. The other was a village school with a predominantly Welsh population;

the researcher chose one class per year group at random and 135 children whose parents consented were recruited. Both schools are situated within deprived areas and have a high percentage of free school meals (33% and 32%; respectively). The demographic characteristics were determined by the schools' willingness to participate. For instance, although deprived areas were not specifically targeted, both schools were situated in such areas.

In total, 169 children participated (75 females and 94 males) ranging in age from 4 to 11 years. Figure 1 shows the age and gender distribution of the participants. The study procedures, which include the screening optometric test and the eye movement recording were conducted on the school premises. Each child participant had the screening optometric test and the eye movement recording on the same day. Children with visually impairing conditions and/or logMAR visual acuity ≥0.3 (with spectacle correction if any), strabismus or manifest refractive errors of more than 8D in the most powerful meridian were excluded from the study.

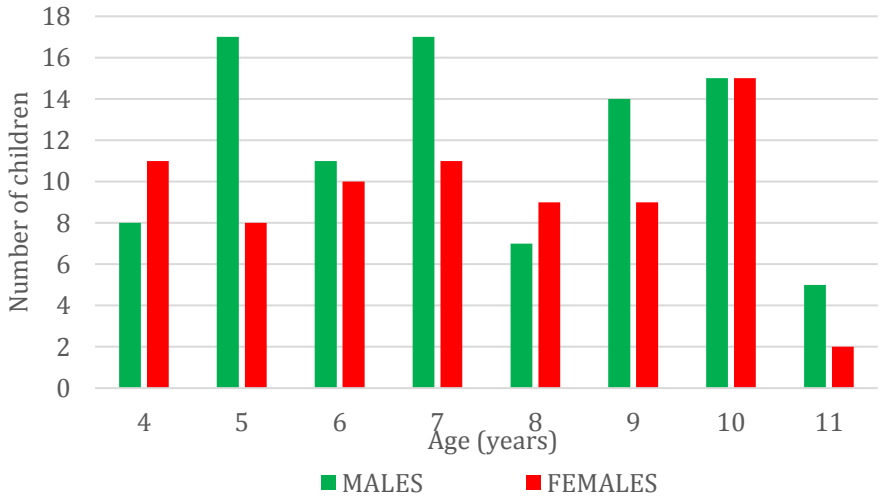

Figure 1. Histogram showing the age and gender distribution of participants.

Children with delayed reading skills

In the UK, children whose reading skills are below the expected level for their age are assigned an Individual Educational Plan (IEP) and receive additional reading support in school. There are other reasons for children having an IEP but this study was concerned only with those having an IEP related to reading. The researchers were masked regarding the IEPs of the child participants. After data analysis was complete, the children's identities were coded, and a teacher of each school indicated by code

which children had an IEP related to delayed reading skills. Six (17%; 3 females and 3 males) and thirty seven children (27.4%; 11 females and 26 males) were identified as having an IEP related to delayed reading skills in the first and the second school, respectively. A total of forty-three children (25.4%; 14 females and 29 males) were identified as having an IEP related to delayed reading skills. A sample size of 40 children with IEP provided 80% power to detect one standard deviation difference between the two groups of children. The sample size and power was calculated at the end of the study using the eye movement data from the children without delayed reading skills. This procedure was conducted to verify the statistical power of the sample to detect differences between both groups.

Screening optometric assessment

The principal investigator recorded the eye movements of all child participants, and conducted the optometric assessment in 71% of the participants. The principal investigator has wide experience in paediatric optometry and tests children routinely in the Special Assessment Clinic, at Cardiff University. The rest of the optometric assessments (29% of children) were conducted by three optometrists who were trained by the principal investigator to perform the same procedures and recording methods. The principal aim of the screening optometric assessment was to exclude any participants with obvious optometric deficits that might affect subject's ability to see the eye movement targets clearly. A refractive error limit was also set as the quality of the eye movement recordings can be influenced by high prescriptions on spectacle correction. Hence the inclusion criteria were logMAR visual acuity $\leq$0.30 with spectacle correction if any, no strabismus or manifest refractive errors of more than 8D.

Visual acuity

Monocular and binouclar distance visual acuity (VA) was measured at 3 m using Kay Pictures logMAR or Keeler logMAR charts. As these two tests have been found to be comparable and in addition, they have been revealed to have good agreement, each child was allowed to choose which of the two he/she preferred.[35] Monocular and binocular near VA was measured with the near version of the child's preferred test. Monocular and binocular VA were measured with habitual spectacle correction, if any. Lighting could not be controlled, but all testing in each school took place in the same room, which was brightly lit.

The examiners occluded the left eye of the participant first with a pair of occluding glasses, positioned themselves 3 m away from the child, and presented the first page of the test. The child was asked to name or alternatively match the first picture of the row of four. This procedure was repeated for smaller sizes of pictures or letters. When a child failed to recognise the first picture or letter from a row of four, the examiner checked the other pictures or letters in the same row. If three or more pictures or letters from a row were correctly named of matched, the examiner presented the next smaller size until reaching the threshold. The procedure was repeated occluding the right eye with the occluding glasses. To assess binocular VA, the examiner presented the last line of pictures or letters that the child was able to see monocularly. The examiner asked the child to name or match all the pictures on that row. If three or more pictures or letters from that row were correctly named or matched, the examiner presented the next smaller size and the procedure was repeated until reaching the child's threshold in binocular conditions. Near Visual acuity was measured by presenting the near version of the child's preferred test at 40 cm. Monocular and binocular visual acuities at near were measured in each participant using the same procedure described for measuring distance visual acuity.

Refractive error

Static distance retinoscopy was used to screen for evident refractive errors. In our study cycloplegic retinoscopy was not possible as the eye movement recordings could not have been performed after dilation. Although Mohindra retinoscopy is the the most appropriate method four our study, this was not possible either as complete darkness could not be achieved in the rooms that the school made available for the study. The result was recorded in sphero-cylinder form for cylinders over 1DC. If the cylinder was <1DC the examiner recorded the spherical refractive error and noted the low cylinder.

Ocular alignment

Cover test was used to evaluate the presence of phorias and tropias at both distance and near. The participants were asked to fixate on a cartoon picture placed in the wall 3 meters away while the examiner assessed the presence of phorias and tropias. The same procedure was performed for near while the participants fixated at on picture printed on a fixation stick and placed 40 centimetres away. The examiners made a judgment of

the magnitude and recovery of the phoria. The researcher recorded: ortho (when no movement of the eyes was detected), and low, moderate of high esophora/exophoria based on the recovery and the direction of the movement.

Objective near Point of Convergence (NPC)

Immediately after performing the near cover test, the participants were asked to keep looking at the picture printed on the fixation stick placed at 40 cm. The participants' attention was attracted by asking him/her to look at a small detail from the picture and at the same time, the examiner slowly moved the fixation stick towards the participants, while observing the participants' vergence movement. Although the distance from the convergence break point to the nose was measured with a tape measure, NPC was recorded if >5cm, but simply noted as <5 cm if the break point was very close. The cutoff of 5cm was chosen in agreement with previously published literature on normative values of NPC.[36]

Stereopsis

A modified version of the Frisby stereotest that contains a demonstration plate was used in our studies.[37] After presenting the demonstration plate, the examiner presented the traditional Frisby plates beginning with the largest disparity plate. Each plate was presented twice, and after each presentation, the examiners hid the plate behind their backs and rotated the plate, so the orientation of the random-dot circle was changed and the same plate was presented. If the participant located the target on two consecutive trials, the next plate (with decreasing disparity) was presented. The end point was reached when the patient failed to locate the target. The testing distance was 40 cm so the disparities recorded by the examiner were 340 sec arc, 170 sec arc or 85 sec arc for the first, second and third plate, respectively.

Accommodation

The accuracy of accommodation was measured in this study as subjective methods that require more cooperation and understanding from the participants have been reported to be challenging to determine accommodative function in children aged 4-11 years.[38] The examiner objectively assessed accommodation accuracy at 25 centimetres using dynamic retinoscopy and the Ulster-Cardiff (UC) cube. The UC cube was placed on the

near point ruler at 25 cm. Questions about the illuminated picture presented were asked during the task to stimulate accommodation and maintain the participant's attention. The examiner placed the retinoscope alongside the target and evaluated the retinoscopic reflex while the participant was looking at the target. If the child was not accommodating accurately and a retinal reflex was observed, the retinoscope was moved further away from (with reflex - underaccommodating) or closer to (against reflex - overaccommodating) the child. The dioptric difference between the target and the neutral reflex was calculated and recorded when a lag/lead of more than +1.00D (i.e. outside the norms) was observed. If accommodation was within the norms[39] (± 1.00D from the UC Cube position), the examiner recorded "within the norms". The accommodative lag was measured in each eye while the child looked at the UC cube binocularly.

Eye movement recording

Eye movement recordings were obtained in binocular conditions using the Tobii TX300 (Tobii Technology, Stockholm, Sweden) eye tracker. This uses the Purkinje reflections to establish horizontal and vertical eye position at 300Hz, with a maximum horizontal gaze angle of ±35º. The system gaze accuracy given by the manufacturer is ±0.5º for monocular and ±0.4º for binocular conditions.[40]

Children were seated 65 centimetres from the screen with their eyes in primary position and facing the centre of the screen. Eye movements were recorded with the child's habitual spectacle correction, if any. A customised child-friendly head stabiliser was used for younger children to maintain their head at a constant distance from the eye tracker/screen throughout. Older children were instructed to keep their head still throughout the test. The eye tracker was calibrated for each participant using the standard Tobii 5 point calibration in which a target moved to 5 points on the screen: the geometric centre and the 4 corners. All test stimuli were presented within the calibrated area.

Saccades

The stimuli used for eliciting saccades were 2º animal cartoons on a white background, appearing at 5º, 10º, 15º and 20º amplitude to the left and to the right without gaps or

overlaps, that is, as each stimulus appeared, the previous one simultaneously disappeared. Presentation order was randomised, and a total of 64 saccades were elicited, 8 saccades for each amplitude and direction. Gellerman-Fellows sequences[41] were combined to avoid eliciting more than three consecutive saccades in the same direction. The participants were instructed to look at the stimuli, but no further instructions were given, so the task was as naturalistic as possible. The presentation time was randomised, between 0.5 and 2 seconds. The task lasted a total of 1.5 minutes.

Visual fixation

The saccadic test was followed by the visual fixation test. A customised 2º animated stimulus was placed in the centre of the screen on a white background. In this case, the stimulus was stationary but continuously changed shape and colour while morphing into different animal cartoons. The participants were instructed to keep looking at the animated stimulus. The stimulus was presented for 8 seconds.

Data Analysis

The eye position traces were analysed offline using custom software written in MATLAB (The Mathworks, Inc., Natick, Massachussets, United States). Eye velocity was obtained by differentiating the eye position over time and smoothed with a 3 window moving average filter, to reduce the additional noise arose from the differentiation process.[42]

Saccades were automatically detected with the adaptive threshold algorithm described by Behrens et al. (2010).[43] The amplitude, duration and peak velocity of all the saccades detected were calculated with a custom program written in MATLAB. The amplitude and the duration of the saccades were obtained by subtracting the time and position at the end of each saccade from the time and position of the start of each saccade detected. The peak velocity was defined as the maximum velocity during the saccade. The program obtained this parameter automatically by using an inbuilt MATLAB function (Max). Only saccades with amplitudes above 4º were used for regression and statistical analysis. Saccades with peak velocities above 700º/s, i.e. saccades larger than 20º[44] (e.g. child looking away) were considered an artefact and removed from the analysis.

Saccadic main sequences

Saccades show a unique feature, which is that they have a consistent relationship between their peak velocity and their amplitude as well as between their duration and their amplitude.[45] These relationships, known as saccadic main sequences, have been used to characterise normal saccades, and they provide invaluable information regarding the saccadic dynamics of an individual.[45] Moreover, saccadic main sequences have been considered a very powerful tool to study saccades, their neurophysiological control, and to determine whether the saccades of an individual are typical or abnormal.[45] For that reason, main sequence duration vs amplitude, peak velocity vs amplitude and peak velocity x duration vs amplitude were studied.

Three plots were obtained for the saccadic task for each child participant. The *Duration vs. amplitude* main sequence was obtained by plotting the amplitude (º) and the duration (ms) of each saccade detected in the X and Y axis, respectively. The slope and intercept obtained from a linear regression on that data were used for statistical purposes. This equation of the linear regression usually has a slope between 2 and 2.7 and intercepts ranging from 20 to 30 in typical adults.[46] Hence, higher values of the slope and intercept indicate slow saccades. For the *peak velocity vs. amplitude* main sequence, the amplitude and the peak velocity of the saccades detected were plotted in the X and Y axis, respectively. A power fit was performed ($y=Ax^n$) for this main sequence for each subject.[46] The parameters A and ^{n} from the power fit were used for statistical purposes. High values found in the power fit parameters suggest abnormally high peak velocities in the saccades.The *peak velocity x duration vs. amplitude* main sequence relationship was plotted and a regression line constrained through the origin was fitted to obtain the ratio Q from the slope of the fitted line.[47] The Q ratio has been suggested to be extremely constant of the order of 1.6-1.9 and values higher than 2 suggest the presence of an interruption in the velocity profile of the saccade.[47]

Fixation stability

The parameters analysed to assess fixation stability throughout the 8 seconds that the stimulus was presented were the total number of saccades during fixation and their mean amplitude.

The saccades during the fixation task were detected using the algorithm previously described. A custom written MATLAB program counted the number of saccades, and calculated the mean amplitude of the saccades throughout the fixation task.

Statistical analysis

The distribution of each optometric/eye movement parameter for each of the two reading ability groups was assessed using histograms and Shapiro-Wilk tests. Parametric statistics were used for visual acuity and refractive error as these were normally distributed. Non-parametric tests were used for the saccadic main sequence and fixation stability as these were non-normally distributed (Shapiro-Wilk $p<0.05$ in >50% of data for both groups).

Optometric parameters

A 2-factor ANOVA (with group as a major factor and accounting for the VA measurements in each eye) was used to compare differences in visual acuity and the absolute spherical refractive error between children with and without delayed reading skills.

Contingency tables and Chi-square tests of independence incorporating Yates correction of continuity were used to assess any association between delayed reading and cylindrical refraction >1DC, presence of phorias, lags of accommodation outside of the norms (>1D)[39], stereopsis <85" or NPC >5 centimetres.

Eye movements

In order to determine whether the quality of the saccadic eye movements were different between children with and without delayed reading skills, multiple Mann-Whitney tests were performed. In order to avoid an increase in type I error,[48] a Bonferroni correction was also performed and a p value <0.01 was considered statistically significant. Two non-parametric independent t-tests were performed to determine whether visual fixation was significantly different between groups of children with and without IEP. A Bonferroni correction was performed in order to control for type I error and a p value <0.025 was considered to be statistically significant.

The analysis described above was used to evaluate differences in eye movement behaviour between children with and without delayed reading. However, it could be the

case that some children with delayed reading have different eye movement parameters to those found in children with good/average reading, but the differences are not large enough to show a significant statistical effect between the two groups. Hence, the upper and lower 95% confidence limits (Mean ± 1.96* SD) were calculated for each eye movement parameter for the group of children without delayed reading skills. Then, the frequency of children with and without delayed reading who had one or more eye movement parameters outside the 'normal' confidence limits was evaluated. Chi-square test of independence incorporating Yates correction of continuity were used to determine the existence of an association between delayed reading and eye movement parameters outside the confidence intervals.

Results

Data from 2 children with nystagmus, 2 children with strabismus and from 2 children in which the eye tracker was unable to calibrate were discarded from the analysis. Hence, data from a total of 120 without delayed reading skills were analysed. No data were discarded for the children with delayed reading skills (n=43).

Optometric parameters

Table 1 shows the mean visual acuity and refractive error (absolute spherical refractive error) found for the children with and without delayed reading skills. The same table presents the statistical p values from the 2 factor ANOVA to compare differences between the two groups. The statistical results showed no significant differences in visual acuity or the absolute spherical refractive error (monocular and binocular) between children with and without delayed reading. Chi-square tests revealed no significant associations between delayed reading and cylindrical refractions >1DC ($\chi^2=0$; $p=1.00$).

The distance cover test revealed that one child without delayed reading skills had a distance phoria (high phoria) and 3 children with delayed reading skills had a distance phoria (2 high and one moderate phorias). Near cover test revelaed that 34 children without delayed reading skills had near phorias (21 low, 3 moderate and 10 high phorias) and 12 children with delayed reading skills had near phorias (8 low, 1 moderate and 3 high phorias). Chi-square tests releavled no significant associations between delayed reading skills and the presence of phorias (distance: $\chi^2=2.75$; $p=0.09$; near:

χ^2=0; *p*=1.00). Moreover, the same test revealed no significant associations between delayed reading skills and the presence of estimated high phorias (distance: χ^2=2.25; *p*=0.113; near: χ^2=0.08; *p*=0.777).

Nine children without delayed reading skills and 4 children with delayed reading skills had NPC >5cm. The mean NPC for children without and with delayed reading skills and NPC >5cm was 7.11cm and 7.25 cm, respectively. Accommodation was found not to be accurate (lags/leads >1D) in 3 children without delayed reading skills (2 children demonstrated a lag (mean 1.75D lag) and one child demonstrated a 1.50D lead), and in 3 children with delayed reading (3 lags; mean 1.66D lag). Chi-squared tests revealed no significant associations between delayed reading and NPC >5 cm (χ^2=0; *p*=0.96), accommodative lags/leads >1D (χ^2=0.75; *p*=0.39), or stereoacuity >85" (χ^2=0.88; *p*=0.35).

Table 1. Mean monocular (RE - right eye; LE - left eye), binocular distance (D) and near (N) VA (±SD), and mean absolute monocular spherical (SPH) refractive error (±SD) in children with and without delayed reading skills.

		RE D.VA	LE D. VA	RE N.VA	LE N.VA	RE SPH	LE SPH
AVERAGE READING	**MEAN ±SD**	**0.02** ±0.08	**0.02** ±0.06	**0.01** ±0.06	**0.01** ±0.04	**0.67** ±0.95	**0.71** ±1.09
DELAYED READING	**MEAN ±SD**	**0.04** ±0.08	**0.02** ±0.08	**0.00** ±0.06	**0.00** ±0.04	**0.58** ±0.66	**0.54** ±0.77
P VALUES		0.554		0.999		0.730	

Eye movement recording

Successful eye movement recordings from 113 (94.16%) and 42 (97.67%) children without and with delayed reading skills were obtained for the saccadic task, respectively. For the fixation stability test, successful eye movement recordings were obtained from 114 (95%) and 41 (95.34%) of children without and with delayed reading, respectively.

Saccades

The mean duration/amplitude main sequence for children with and without delayed reading are represented for illustration purposes in Figure 2. It can be observed that the saccadic duration relationship does not different between children with and without delayed reading skills. Hence, the functions representing the relationship between the duration and the amplitude of the saccades in children with and without delayed reading

skills overlap. The median and the 25th and 75th quartiles for the duration/amplitude main sequence are presented in Table 2. Mann-Whitney tests confirmed no difference in slope (Z_{153}=-0.964; p=0.335) or intercept (Z_{153}=-0.076; p=0.939).

Similar results were found for the other main sequence functions: peak velocity/amplitude and peak velocity x duration/amplitude. The functions overlap for both groups and no evident differences are observed. Table 2 presents the median and the 25th and 75th quartiles for the peak velocity x duration/amplitude main sequence parameters, and the Q ratio for the two groups of children. Mann-Whitney tests confirmed no significant differences for any of the main sequence parameters A (Z_{153}=-0.12; p=0.90), n (Z_{153}=-0.76; p=0.44), and Q ratio (Z_{153}=-2.18; p=0.03).

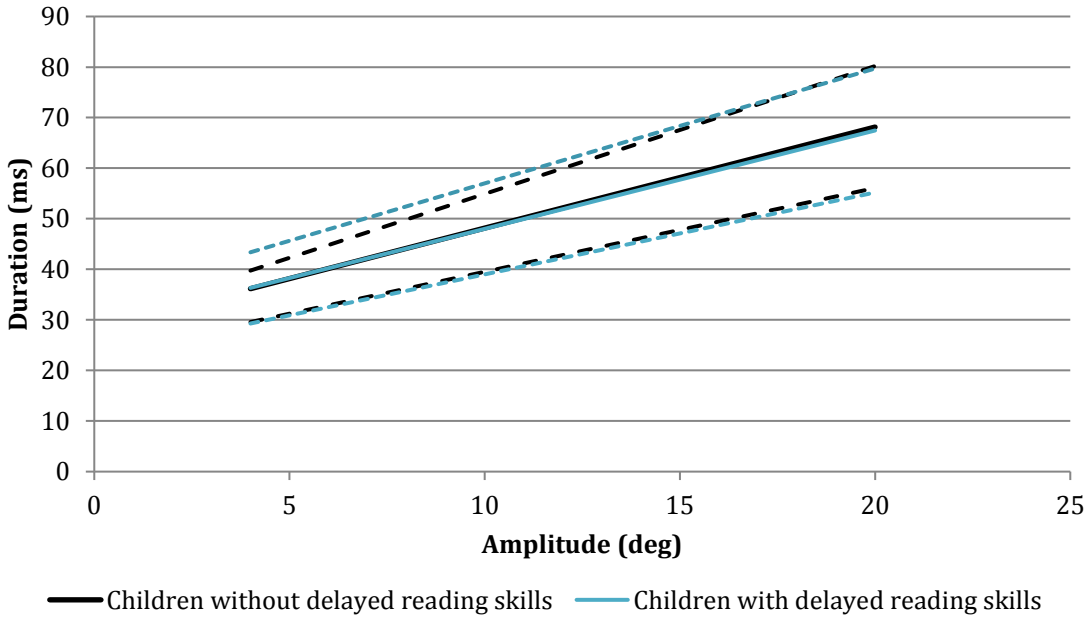

Figure 2. Duration/amplitude main sequence for children with and without delayed reading. The dashed line represents the mean duration/amplitude main sequence and the continuous lines represent ±SD for each group.

Table 2. Main sequence parameters for children with and without delayed reading skills. Values are medians for all participants in each group with the corresponding 25th and 75th quartiles.

	Duration/Amplitude main sequence		Peak velocity / Amplitude main sequence		Peak velocity * duration/ Amplitude main sequence
	Slope	Intercept	A	n	Q ratio
Children without delayed reading	2 (1.78-2.20)	27.98 (24.59-31.94)	140.28 (119.88-159.81)	0.39 (0.35-0.44)	1.61 (1.56-1.68)
Children with delayed reading	1.91 (1.62-2.22)	28.19 (24.08-31.66)	142.37 (116.08-165.14)	0.41 (0.35-0.45)	1.66 (1.66-1.73)
p	0.335	0.939	0.90	0.44	0.03

Fixation stability

Figure 3 shows the median number of saccades and their amplitude for children with and without delayed reading skills. It can be observed that both the number of saccades, and their amplitude are very similar between the two groups of children.. Mann-Whitney non-parametric statistical tests confirmed no significant differences in the number of saccades (Z_{153}=-0.738; p=0. 460) and their mean amplitude (Z_{153}=-0.721; p=0.471) between both groups

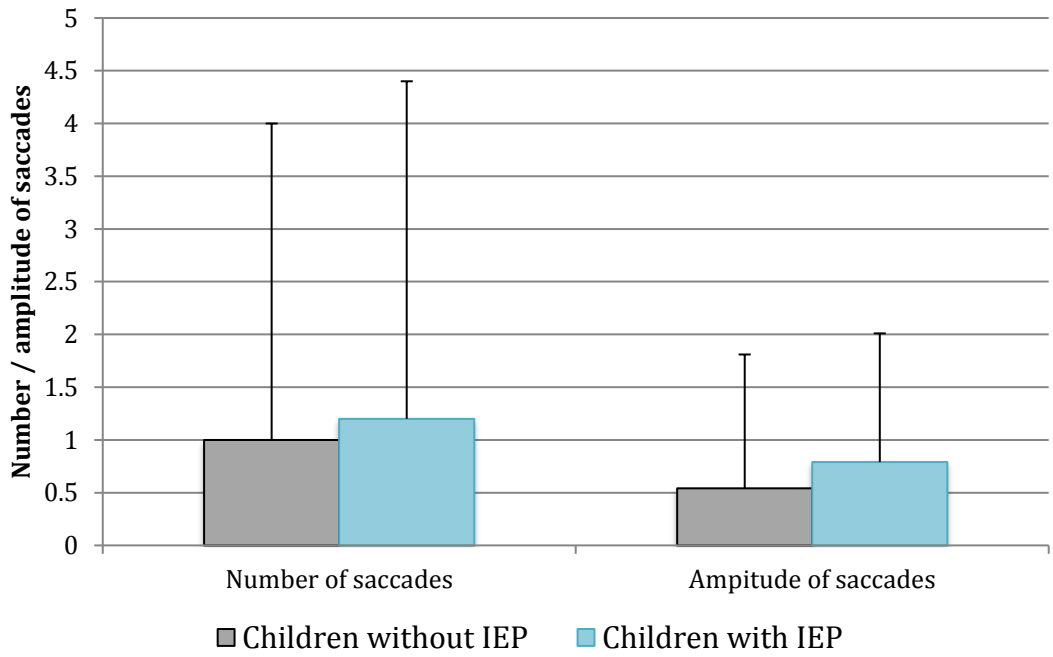

Figure 3. Fixation stability parameters for children with and without delayed reading skills. Values are medians for all participants in each group and the error bars represent the upper quartile (75th percentile).

Individual comparisons between children with and without delayed reading skills

One or more of the five main sequence parameters of children with delayed reading were more frequently outside the 95% confidence limits for their age (21.45%) than was the case for children without delayed reading (13.27%), but the difference was not significant (χ^2 =0.995; p=0.319). Similarly, there was no association between delayed reading and an increased number or amplitude of saccades during the fixation stability task (χ^2=0.00; p=1.00). Approximately 7% of children with and without delayed reading had one or both fixation stability parameters outside the 95% confidence limits.

Finally, there was no significant association between delayed reading and parameters being more frequently below the 95% confidence limits. Hence, 39.13% and 20% of the main sequence parameters outside the norms were found to be below the 95% confidence interval in children with and without delayed reading, respectively (χ^2=0.448; p=0.503), and all the fixation stability parameters found outside the norms (only 7% of children with and without delayed reading skills had fixation parameters outside the norms) were above the 95% limit in both groups (χ^2=0.00; p=1.00).

Discussion

Although it is well established that there are differences in eye movements during reading between good/average readers and poor readers, debate continues about the causality or the effect of oculomotor deficits in reading difficulties.[e.g.19, 20, 49] In general, individuals with good/average reading skills make fewer fixations and regressions and also fixations are briefer than in poor readers[e.g.4, 6, 9, 10]. However, it can be argued that these differences might be related to text difficulty,[8, 11] text format[21, 49] or higher order linguistic characteristics such as syntactic difficulty and/or plausibility[21, 50] rather than to oculomotor deficits. For that reason, findings from eye movement behaviour during reading in individuals with different reading abilities should be cautiously interpreted, because reading is a complex process that not only involves effective oculomotor control but also requires an effective integration of sensory, perceptual and cognitive information.[51] Consequently, an increased number of saccades or an increased fixation duration during reading in children with delayed reading skills may indicate difficulties in other visual or non-visual aspects rather than poor oculomotor control. Hence, this study investigated the saccadic main sequences and fixation stability in children with

and without delayed reading skills during non-reading conditions in order to provide a quantitative evaluation of “pure” oculomotor performance in these two groups of children.

Our results showed that the saccadic main sequences obtained from children with delayed reading skills were not different to those found in children without delayed reading skills. In addition, the saccadic main sequences, which describe the relationship between different saccadic features and are a widely accepted method to characterise normal saccades, were shown to be typical in children with and without delayed reading skills, and therefore describe "normal" saccadic control in both groups. Although saccades described here were obtained using a very different saccadic task than those presented in previous studies evaluating saccades in children with delayed reading skills during non-reading tasks[2,19] our results are consistent with previous literature, further supporting no differences in saccadic performance between children with and without delayed reading.

Most studies investigating eye movements in individuals with delayed reading skills during non-reading tasks have mainly focussed on saccades rather than fixations. However, as fixations can also be considered an important part of the reading process, this study has also investigated fixation stability. Although the number and amplitude of saccades during fixation were the only parameters used to assess fixation stability, these were not different between the groups studied. To our knowledge, this is the first study to investigate fixation stability in children with delayed reading skills during a non-reading task. Notwithstanding, there is a study that quantitatively evaluated fixation stability in typical developing children[32] and the number and amplitude of the saccades reported in here in both groups of children seem to be similar to those reported by Ygge et al. (2005),[40] confirming that our child populations were not different from previously studied samples.

Comparison across groups can mask differences in individual performance. For that reason, eye movement parameters from each child were individually compared to the norms (95% confidence limits) obtained from children without delayed reading skills. As expected, some children without and with delayed reading have their eye movements outside the norms, but there was no significant difference between the

groups. However, the main limitation of this study is that, due to a confluence of issues in respect of ethical approvals and confidentiality, we were unable to further investigate the common characteristics that might be present in children with delayed reading and eye movements outside the norms, as the only information we held about the children recruited from the schools was their age and whether or not they had an IEP related to delayed reading skills. No other details related to the severity of the reading/learning related difficulty and co-occurring difficulties/conditions that could have an impact on their eye movement performance could be obtained during the research. There are three main reasons why this information was not available for our study. First, as one of the principal objectives of this project was to investigate eye movements in children with delayed reading, the protocol submitted and approved by the School of Optometry and Vision Sciences Research and Audit Ethics Committee stated that only children with reading related difficulties would be identified from the sample. Consequently, after the results suggested, that some (but not all) children with IEP had eye movement differences when compared to controls, we were limited by our ethical approval with regard to the information we could gather from these children. Second, even after the parents gave consent for their children to take part in the study, the schools were very sensitive to disclose any information with regard to the children's difficulties and conditions. Finally, while the schools can provide detailed information related to the severity of the reading difficulty, the schools are not in a position to provide detailed information about other conditions/difficulties that the children had. In order to acquire this information, it would have been necessary to directly contact the parents of the children and obtain their consent to access their children's medical records through either a general practitioner or paediatrician. Such additional procedures were not contained in the study protocol that received ethical approval, and therefore could not be undertaken. In any case, children with developmental disorders such as autism and coordination disorder have been found to have normal basic oculomotor control (i.e. saccadic duration, gain, velocity, etc.) but abnormal saccadic latencies indicating visual processing deficits rather than oculomotor control deficits.[31] Hence, the parameters chosen in this study are less likely to be affected by developmental disorders than parameters such as error rate and latency. In addition, our sample size allows to detect differences between groups of one standard deviation or more. Therefore, if smaller differences between groups are considered clinically important, a larger sample size is needed. However, the medians and $25^{th}/75^{th}$ quartiles from both groups were very

similar and it could be argued that differences smaller than one standard deviation are unlikely to be functionally important. Finally, our study was aimed to investigate differences in eye movement control that could be clinically detected by eye care practitioners and not small differences that could only be detected using eye movement recordings. Hence, future research with larger sample sizes is needed in order to study smaller differences in eye movement control between these two groups.

Other than eye movement difficulties, vision problems such as refractive error and accommodation or vergence deficits can also interfere with the reading process. Moreover, while vision deficits may not be the main cause of reading difficulties,[52] it is reasonable to suggest that these play an important role in reading abilities. Hyperopic refractive error has been found to be strongly correlated with delayed reading skills and lower academic performance in children.[52, 53] In addition, a recently published study also found a correlation between astigmatism and reading difficulties.[24] Our purpose was to determine any eye movement differences between good and poor readers, not to investigate subtle optometric differences. In our analysis, therefore, we concentrated on gross optometric functions (such as reduced acuity, manifest hyperopia or accommodative lag) that could have influenced performance on eye movement testing. Our study did not find a significant difference in the spherical or cylindrical refractive error between children with and without delayed reading. Unlike the above mentioned studies, non-cycloplegic retinoscopy was performed in the current study, so hyperopia levels could have been under-estimated. Finally, none of the optometric measures obtained that includedr VA, accommodation accuracy, estimated phorias and stereopsis were associated with delayed reading. We cannot of course exclude other functions that could be contributing to poor reading, but we can, we believe, exclude eye movement control. Similarly, further research is needed to investigate subtle optometric differences between children with and without delayed reading skills. Although we anticipate controversy with regard to these results, they are in line with those found by a number of authors.[54, 55]

Conclusion

These findings provide additional evidence to support the view that in general, reading difficulties are not associated with eye movement deficits and the gross optometric

parameters studied in here (refractive errors obtained using non-cycloplegic distance retinoscopy, distance and near VA, estimated phorias, accommodation accuracy and stereopsis), and further question interventions that target the visual system, which are generally non-evidence based.

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